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Soldier/Hardware-in-the-loop Simulation-based Combat Vehicle Duty Cycle Measurement:
Duty Cycle Experiment 2

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Prior Work

- Prior experiment DCE1, Nov 2005
- 06S-SIW-080

Human-in-the-loop Simulation-based Combat Vehicle Duty Cycle Measurement: Duty Cycle Experiment 1

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Keywords:
Hybrid electric power train, duty cycle, motion base, human-in-the-loop

ABSTRACT: *This paper describes the use of human-in-the-loop motion-based simulation to measure the duty cycle of a hybrid-electric combat vehicle. The project is part of TARDEC's Power & Energy program and it is motivated by the need to accurately understand the duty cycle of a hybrid-electric combat vehicle in order to properly design and size its individual components. The project seeks to assess the duty cycle both in terms of mobility-type loads as well as combat-type loads to include pulse-power systems. After introducing the project, the paper describes the simulation environment which was assembled to measure such a duty cycle. It describes the factors which drove the choice of particular components and how those components contribute to the simulation as a whole. It describes the experiment design to include the choice of scenario, terrain, and operator tasks. It discusses the test results and briefly discusses on-going and future work.*

1. Introduction

The Army has been developing hybrid-electric propulsion technology because of its many advantages, some of which are better fuel efficiency and the ability to maintain "silent" operations. Since, many alternative implementations are available for such a system, the Army has developed a Power and Energy System Integration Laboratory (PE-SIL) to combine components into a series hybrid-electric power system. It is currently being used to investigate hybrid-electric propulsion for a tracked 24-ton Future Combat Systems (FCS) manned ground vehicle.

Since the hybrid-electric power system is the sole source of energy for mobility, survivability and lethality on an FCS vehicle, both the supply and demand of energy must be managed. In order to effectively design a power management system and properly size the components, accurate estimates of power loads throughout the complete range of operations are required. Little data exists on power flows for vehicles involved in future military operations. What is known of FCS operations to date has been determined from inventive thinking, combining concepts of operations and extrapolation of the current state of technology. Simulations intended to measure the power demand of a vehicle system in tactical operations are called *duty cycle experiments* (DCEs); these duty cycle experiments combine engineering-level power supply models with performance-level models of power-consuming devices in a warfighter simulation. The intent of these DCEs is to establish standard vehicle

CHPS SIL

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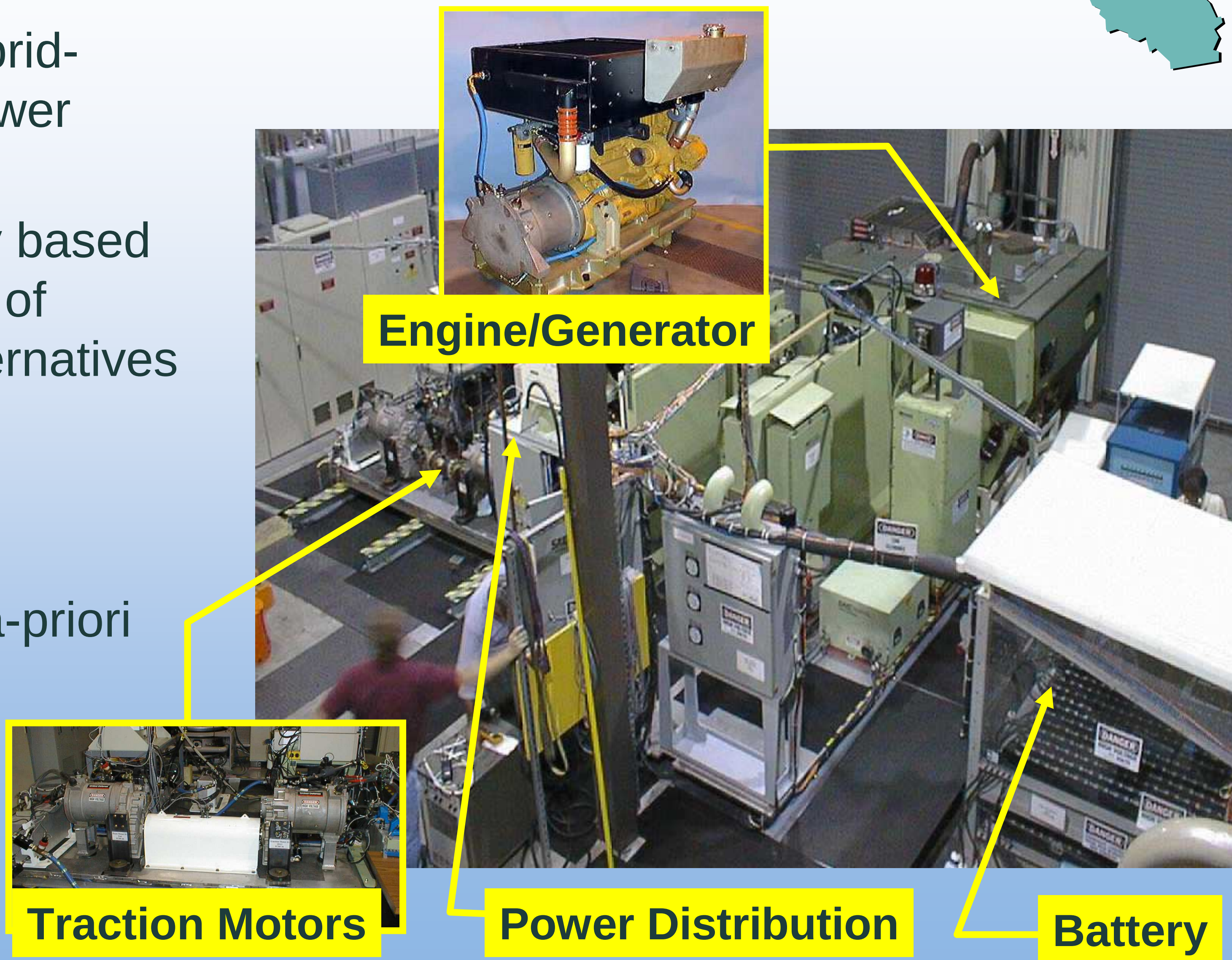
- Series Hybrid-electric power system
- Laboratory based evaluation of design alternatives
- Driven by automated controller
- Requires a-priori duty cycle



Duty Cycle: Definition

- A military vehicle's *duty cycle* is specific to the mission and platform type but is a design- and configuration-independent representation of events and circumstances which affect power consumption.
- Such events and circumstances encompass (1) vehicle operation along the course such as speed, grade, turning, turret/gun activity, and gun firing plus (2) external scenario components that affect power consumption like incoming rounds, ambient temperature, and soil conditions.
- The event inputs can be distance based when the vehicle is moving or time based when the vehicle is stationary, or even triggered with some other state condition.

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Ride Motion Simulator

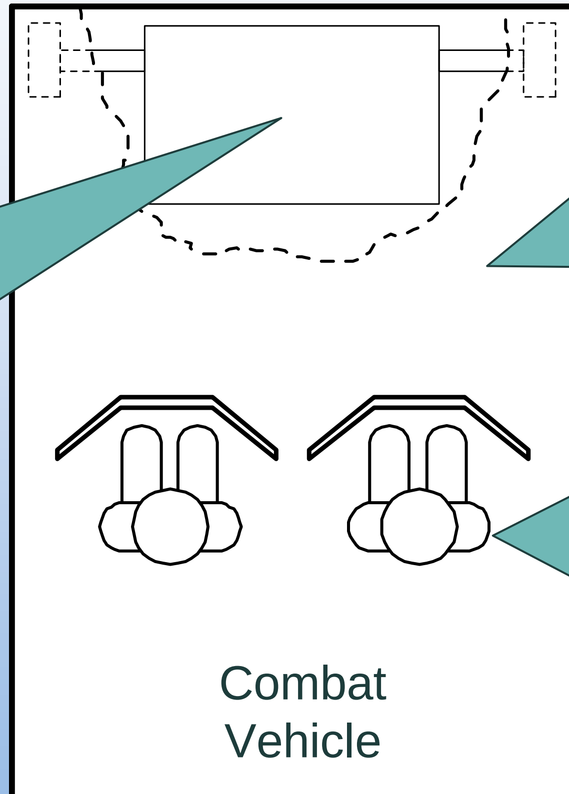
- Man-rated motion base simulator
- Integrated immersive simulation environment
- Real-time vehicle model
- Integrated CAT Crewstation
- Ideal facility for capturing soldier behavior (i.e. duty cycles)

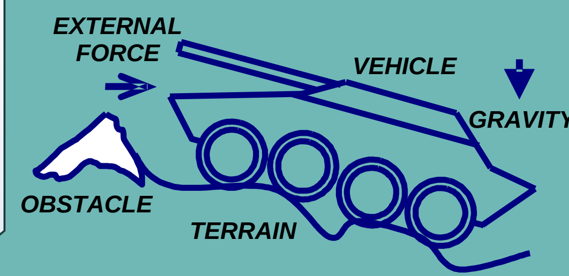
Duty Cycle Experiment 2 (DCE2)

- Measure the "duty cycle" of FCS-MCS-like vehicle
- Use a relevant combat scenario.
- Implement the driver and gunner stations of the vehicle
- Seamlessly operate the CHPS SIL in the loop
- Experienced soldiers as participants
- Measure mobility loads.
- Measure non-mobility loads.
  - Gun/Turret motion
  - Defensive system activity
  - Weapon activity

SIL/RMS Integration Concept

Power Train (SIL)





Vehicle Dynamics and Terrain (TSL)

Driver/Gunner (TSL)

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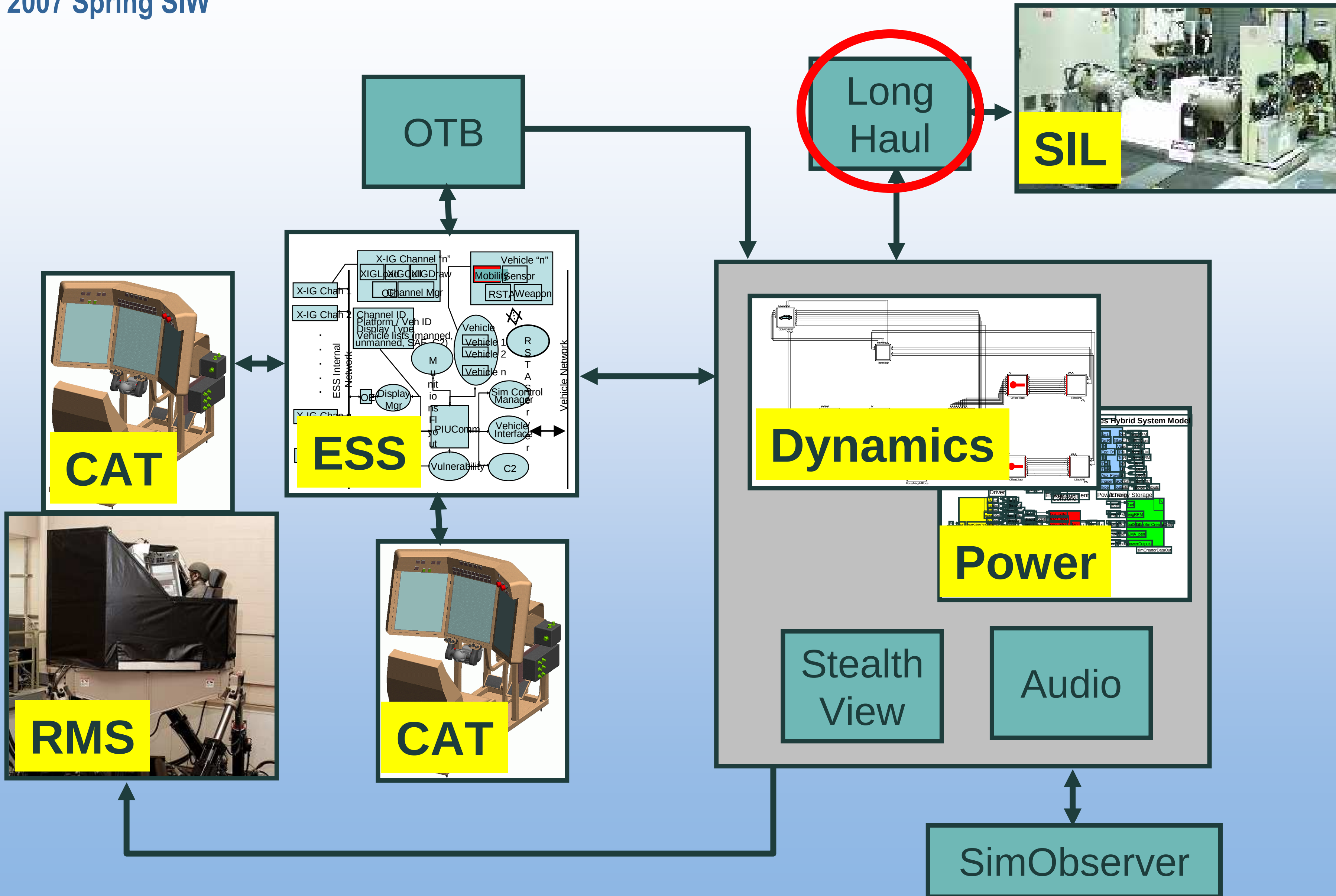
DCE2 Top Level Design



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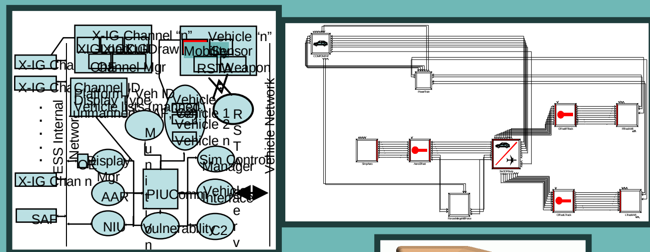
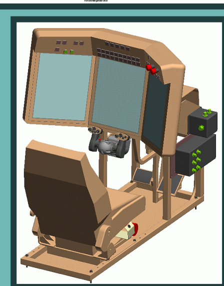
Geography of Assets: *2,450* miles apart*





RMS/CAT/ESS/Dynamics

TSL
Warren, MI

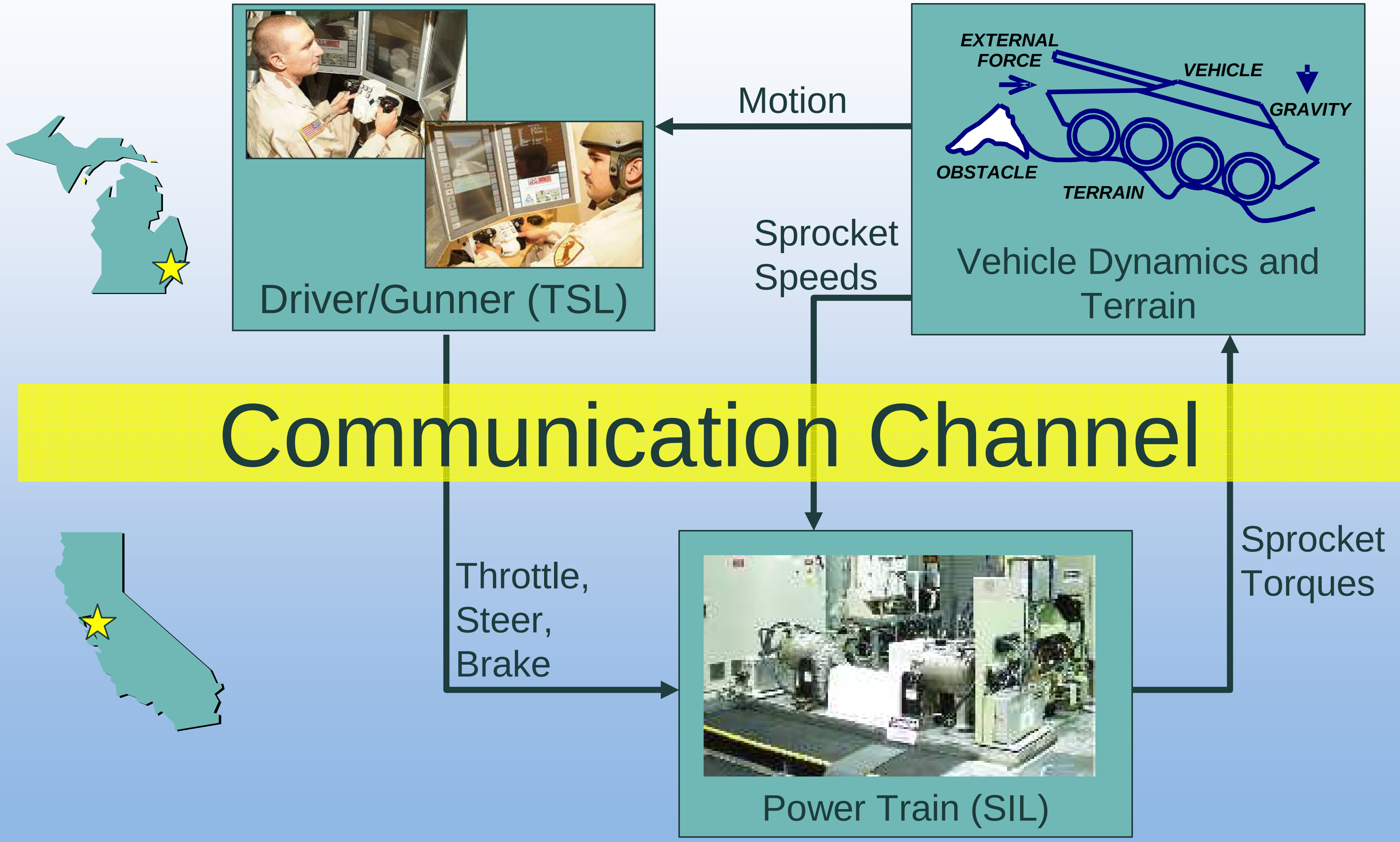
P&E SIL
Santa Clara, CA

Power Train (SIL)

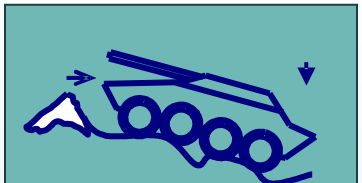
Driver/Gunner (TSL)

* As reported by MapQuest®

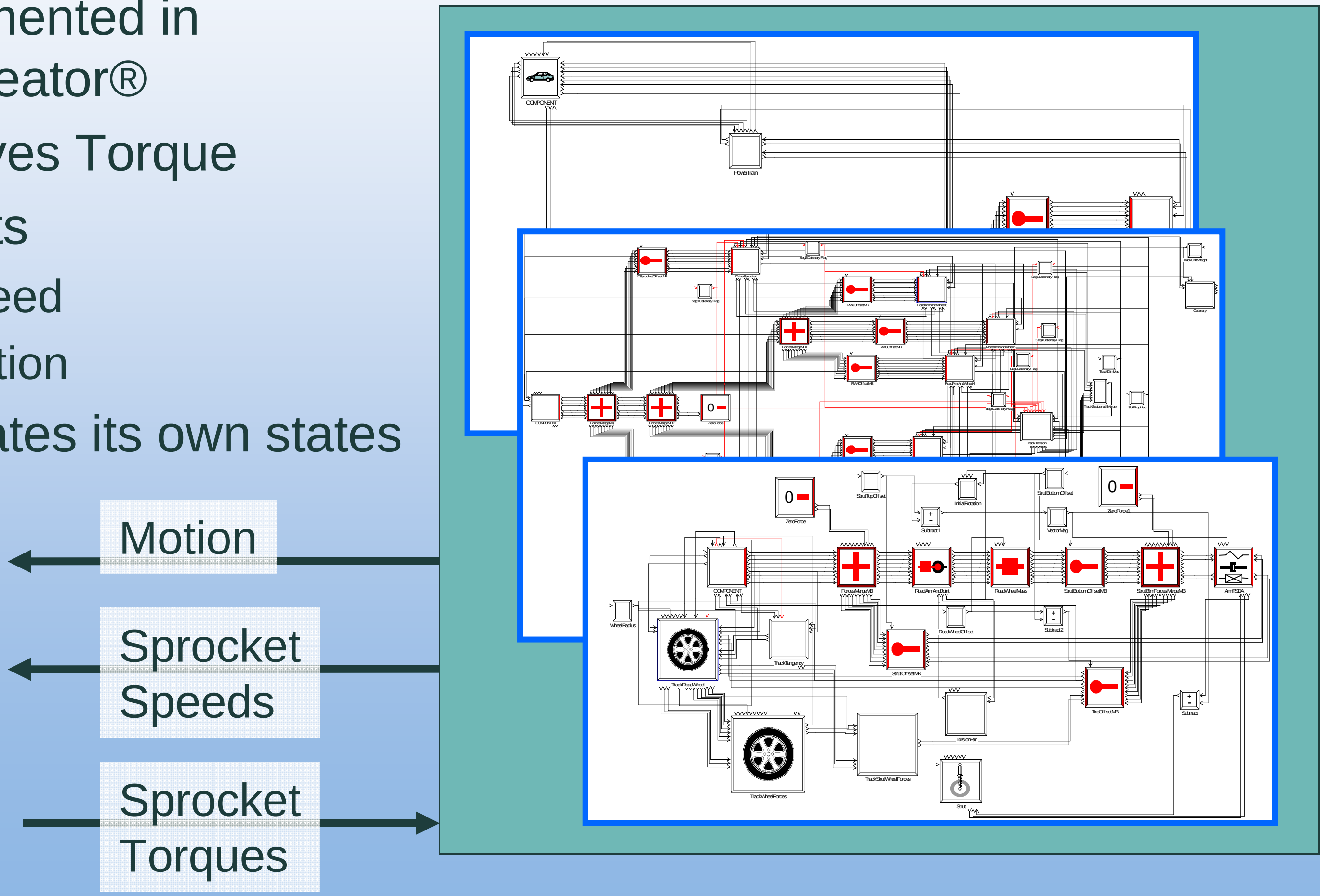
Interconnections



Vehicle Dynamics and Terrain



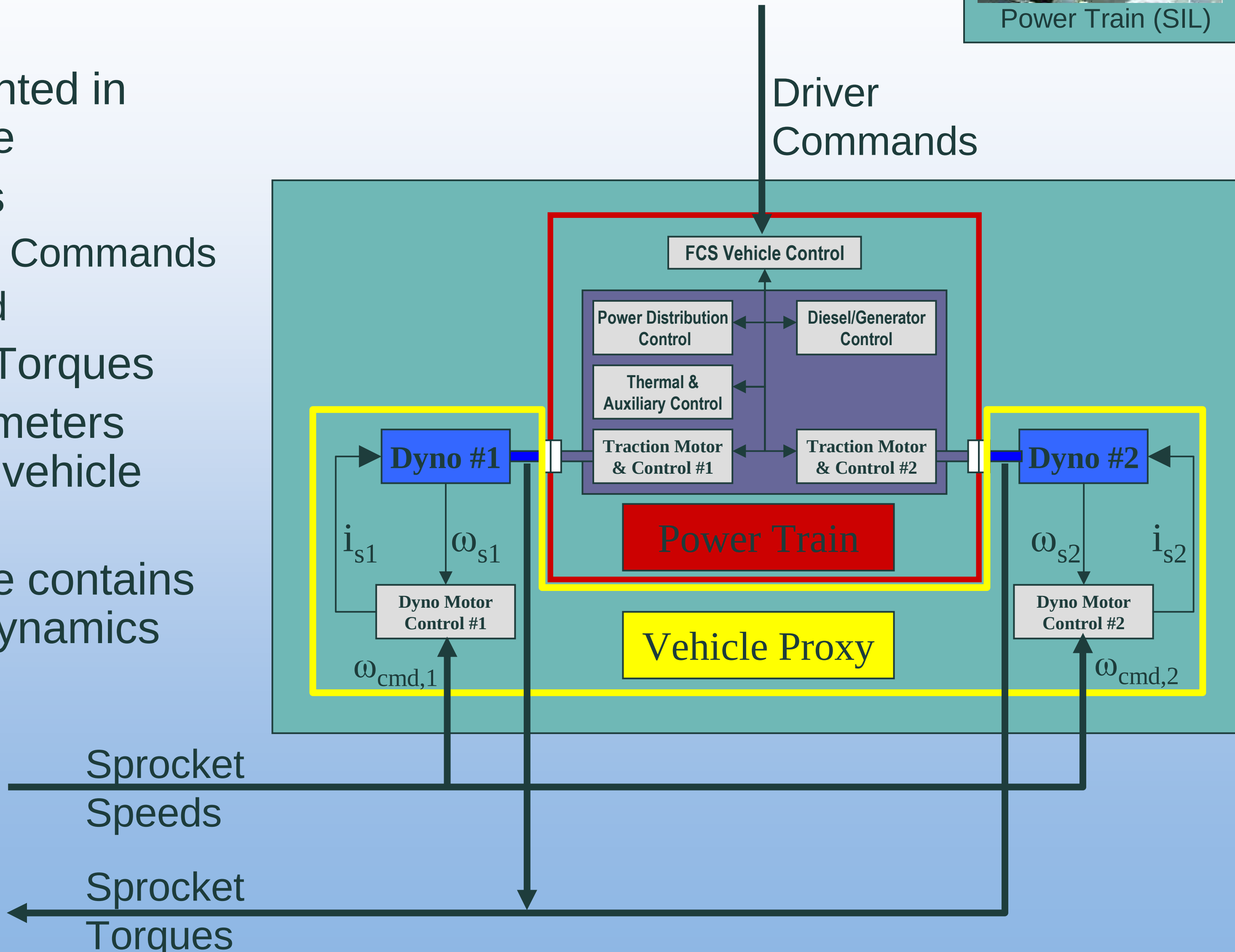
- Implemented in SimCreator®
- Receives Torque
- Outputs
  - Speed
  - Motion
- Integrates its own states



Power Train


Power Train (SIL)

- Implemented in Hardware
- Receives
  - Driver Commands
  - Speed
- Outputs Torques
- Dynamometers serve as vehicle proxy
- Hardware contains implicit dynamics



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Communication Channel

Modem (56k bps)

- Analog/Digital
- Dedicated channel
- Connection-based
- Reliable??
- No firewall
- Noise-based corruption
- **~350 ms round trip**
- **1.4% loss rate**

Internet

- Digital
- No dedicated channel
- Packet-based
- Moderately Reliable
- Firewall configuration required
- Dropped packets
- **~94 ms round trip**
- **0.1% loss rate**

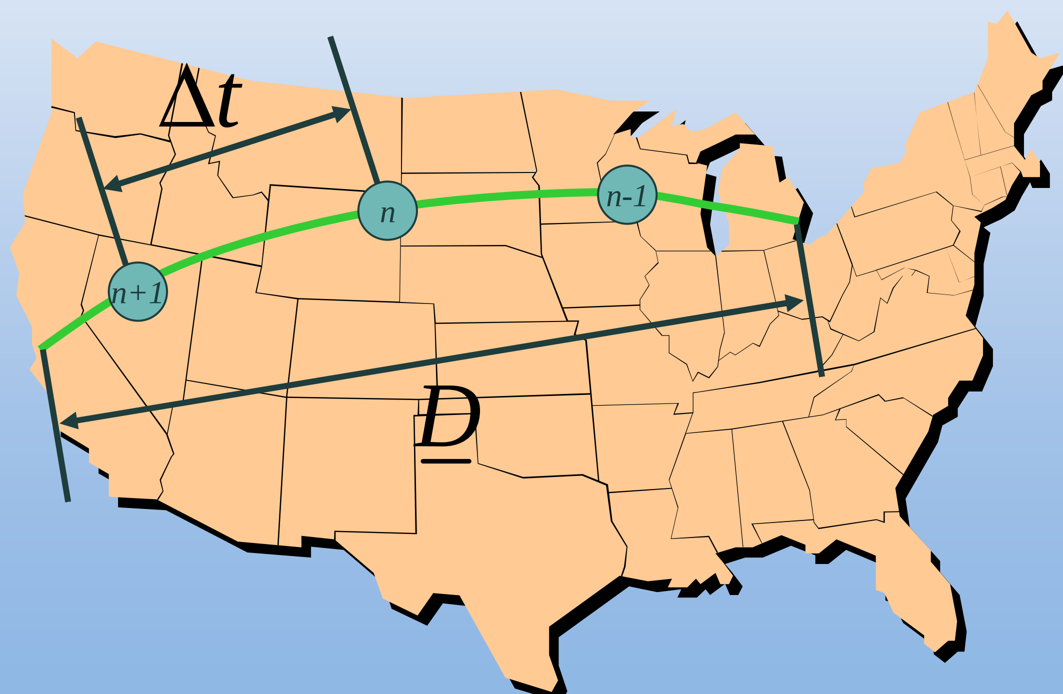
Protocol Choice

TCP $\Delta t \gg \underline{D}$

- (Virtual) Connection
- Layered on IP
- Stream
- Reliable

UDP $\Delta t \ll \underline{D}$

- Connectionless
- Layered on IP
- Packet
- Unreliable



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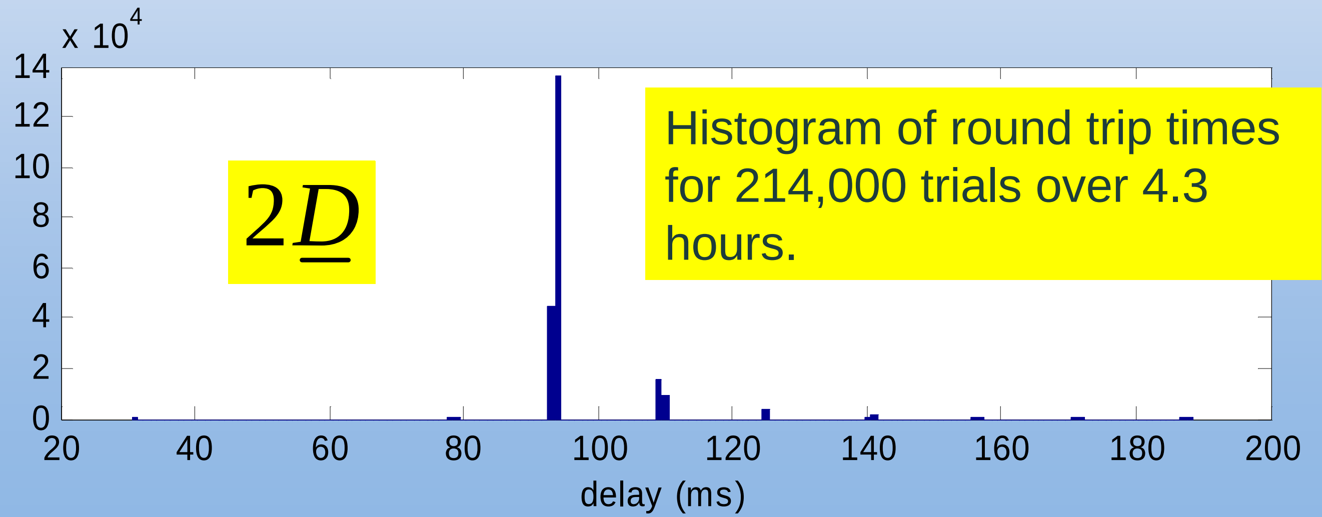
UDP Performance

- Round trip times
  - 33 ms to 188 ms
  - Most at 94 ms
  - Limit 26 ms
- 209 packets dropped
- Vehicle dynamics ~2 ms
- SIL ~10 ms

- Problems
  - Substantial delay
  - Delay jitter
  - Data loss

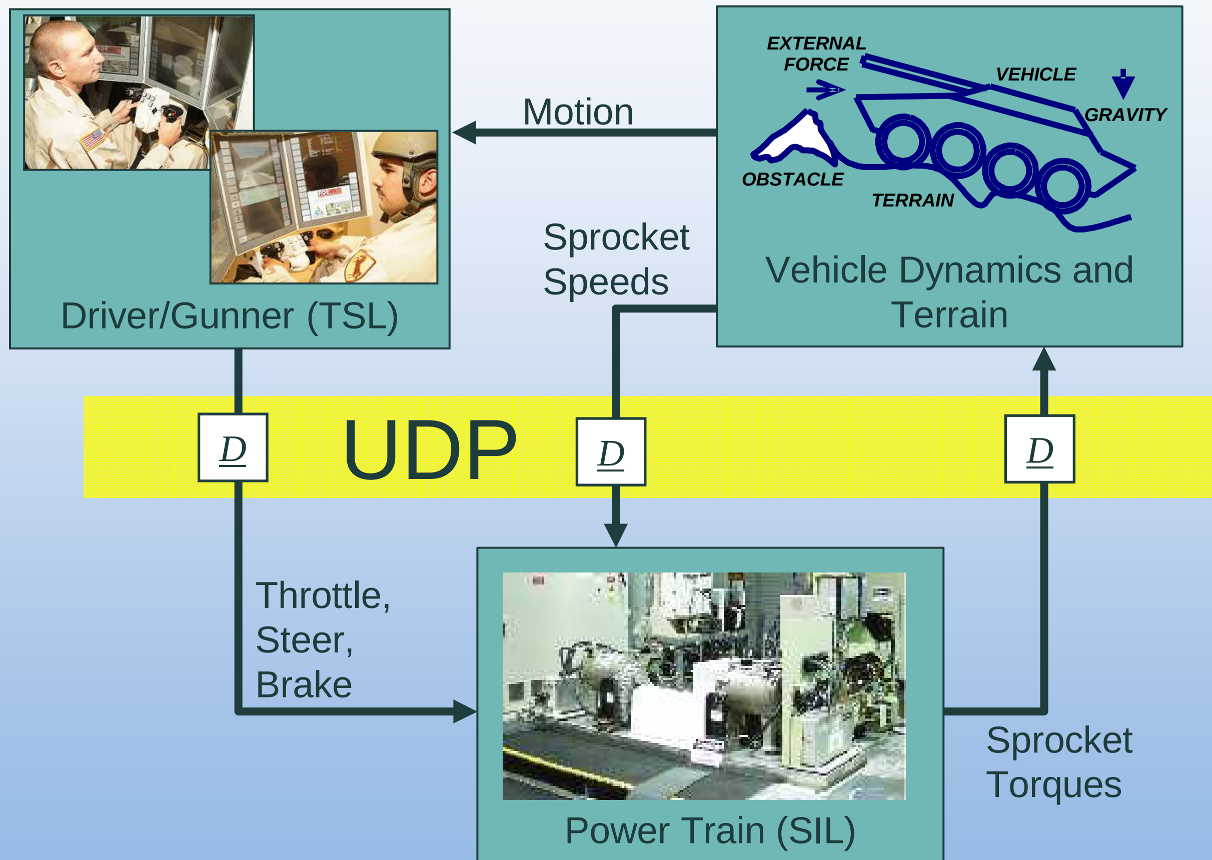
→ System Instability

$\underline{D}$ is a random variable



Simple Approach

- Delay > Dynamics response
- Delay > SIL response
- Simulator response
  - Driver → Motion
  - Increased by *2D*
- Safety risk to driver
- Damage risk to SIL
- Experimental quality degraded
- Potential instabilities



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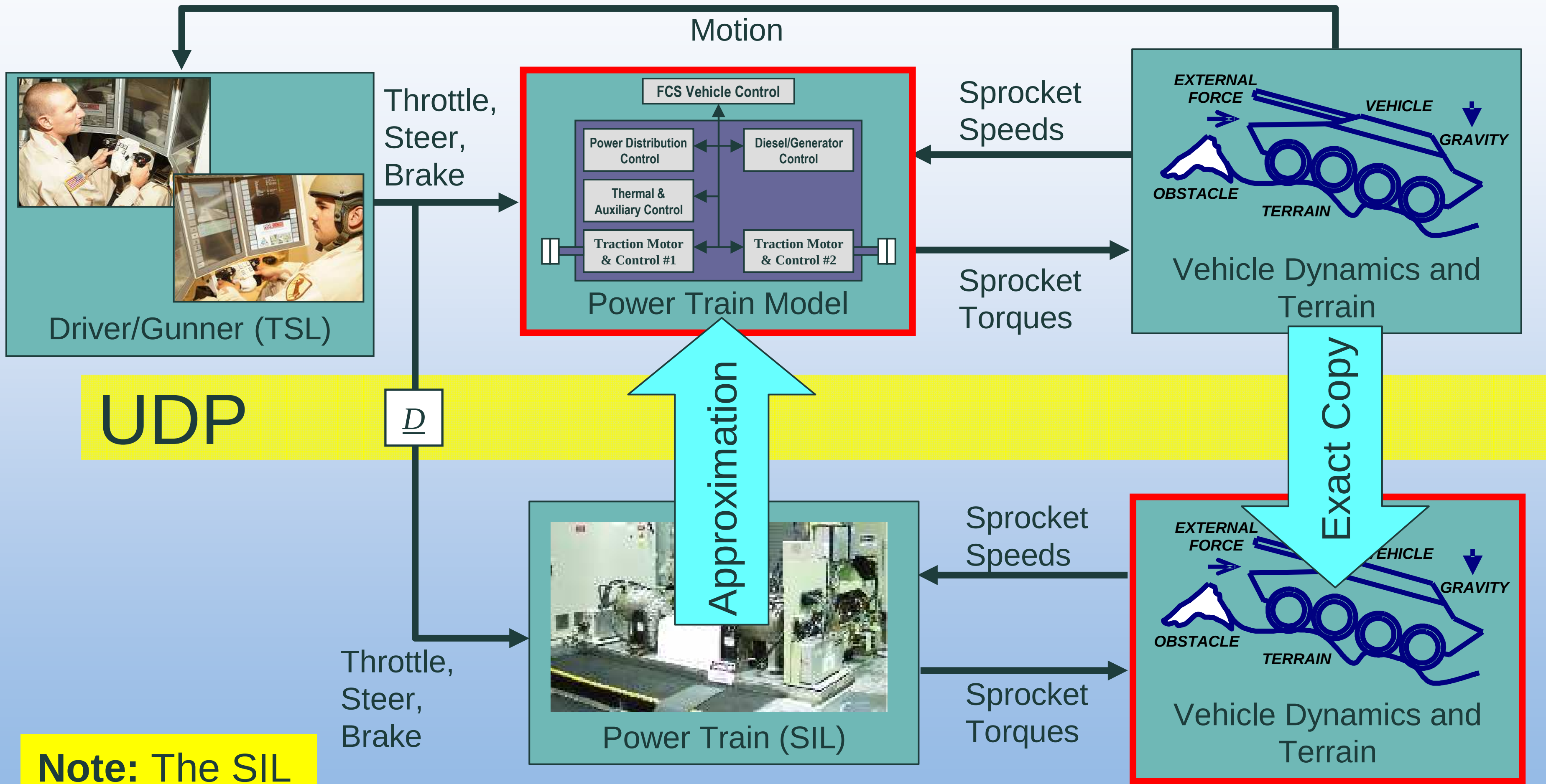
Parallel Simulation Approach



Note: The SIL always lags the TSL by *D.*

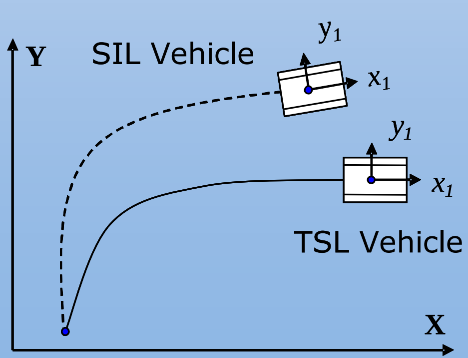
Parallel – Evaluation

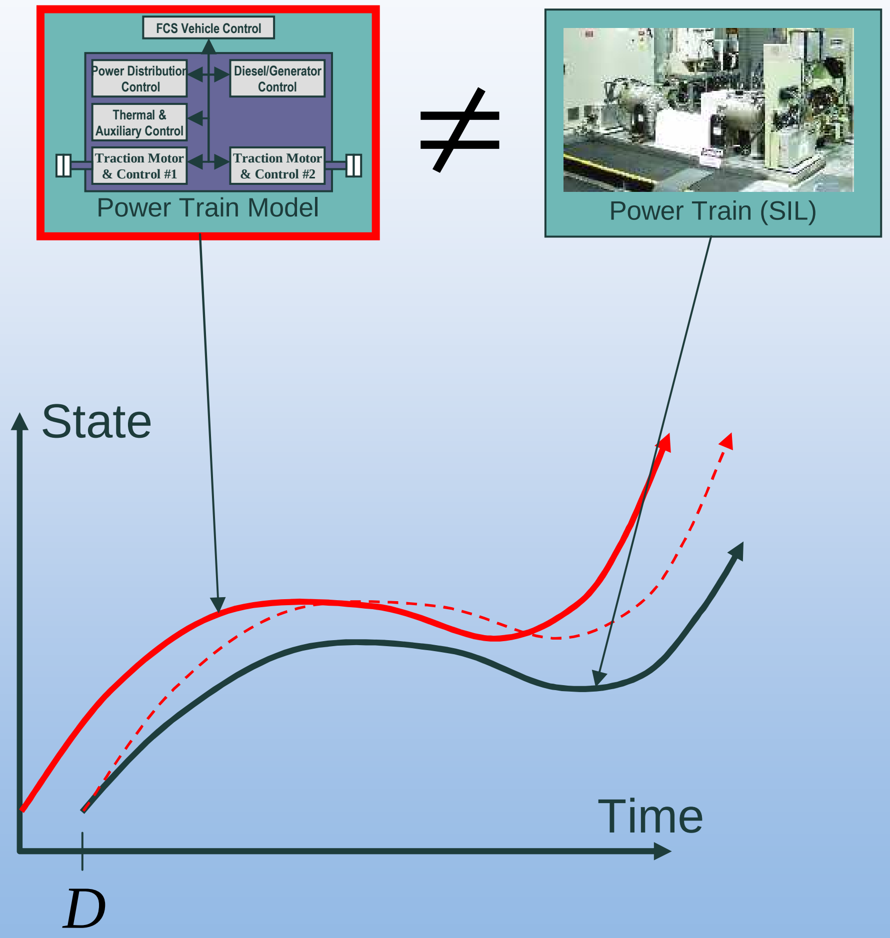
Pros

- SIL will receive proper commands delayed by D
- Immediate response
- The GVSL and SIL are not coupled

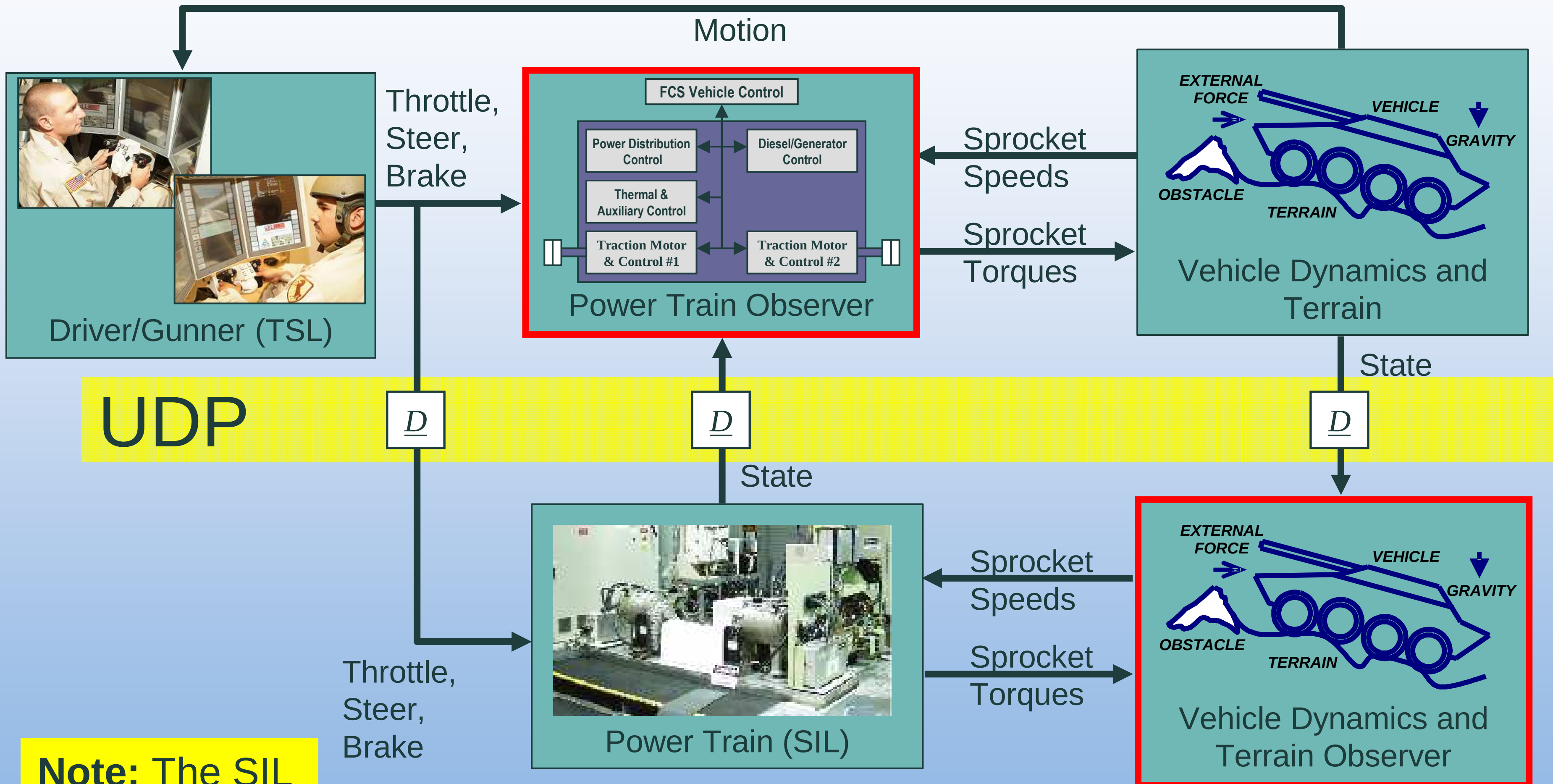
Cons

- The power train model does not exactly match the SIL
- The GVSL and the SIL will tend to drift apart over time.



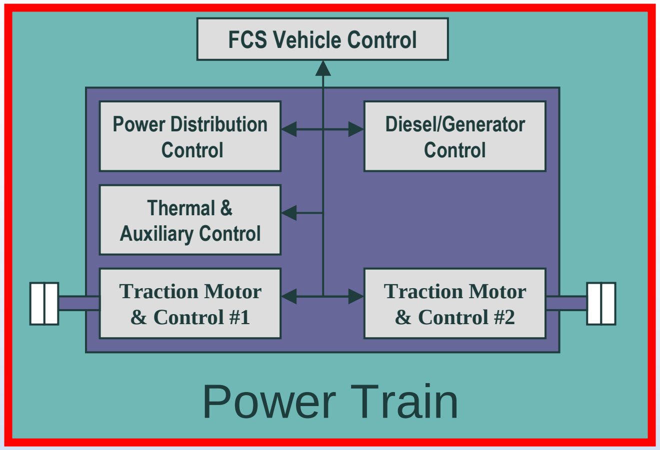


Observer-Based Approach



Note: The SIL always lags the TSL by *D.*

Power train dynamics



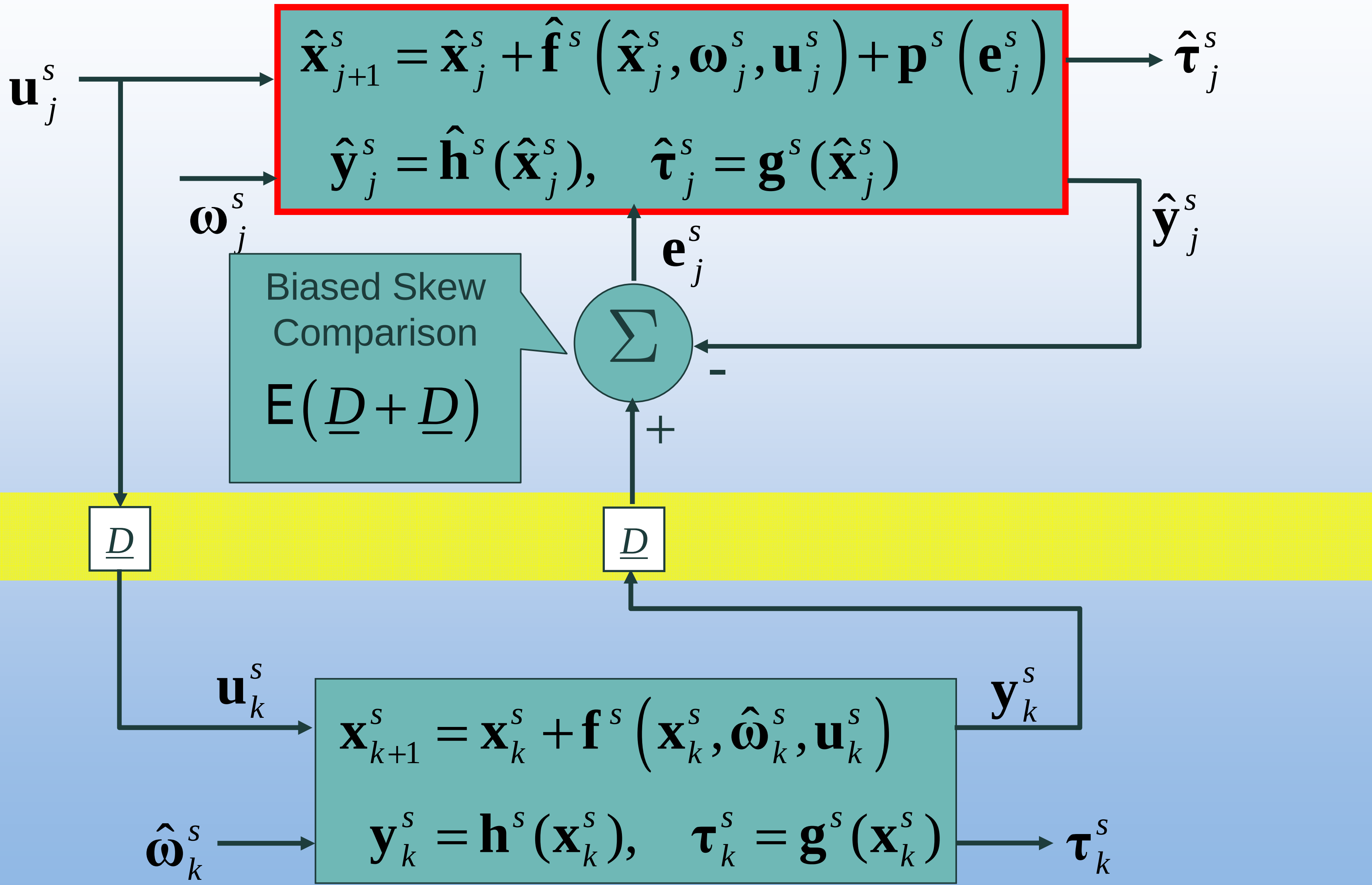
$$\mathbf{u}_k^s = \begin{bmatrix} t \\ s \\ b \end{bmatrix}, \qquad \boldsymbol{\omega}_k^s = \begin{bmatrix} \omega_{\mathrm{L}} \\ \omega_{\mathrm{R}} \end{bmatrix}$$

$$\mathbf{x}_{k+1}^s = \mathbf{x}_k^s + \mathbf{f}^s\left(\mathbf{x}_k^s, \boldsymbol{\omega}_k^s, \mathbf{u}_k^s\right)$$

$$\mathbf{y}_k^s = \mathbf{h}^s(\mathbf{x}_k^s), \quad \boldsymbol{\tau}_k^s = \mathbf{g}^s(\mathbf{x}_k^s)$$

$$\mathbf{y}_k^s = \begin{bmatrix} SOC_{\mathrm{b}} \\ V_{\mathrm{bus}} \\ \omega_{\mathrm{e}} \\ \ell_{\mathrm{f}} \\ T_{\mathrm{b}} \\ \vdots \end{bmatrix}, \qquad \boldsymbol{\tau}_k^s = \begin{bmatrix} \tau_{\mathrm{L}} \\ \tau_{\mathrm{R}} \end{bmatrix}$$

Power Train Observer (skewed)



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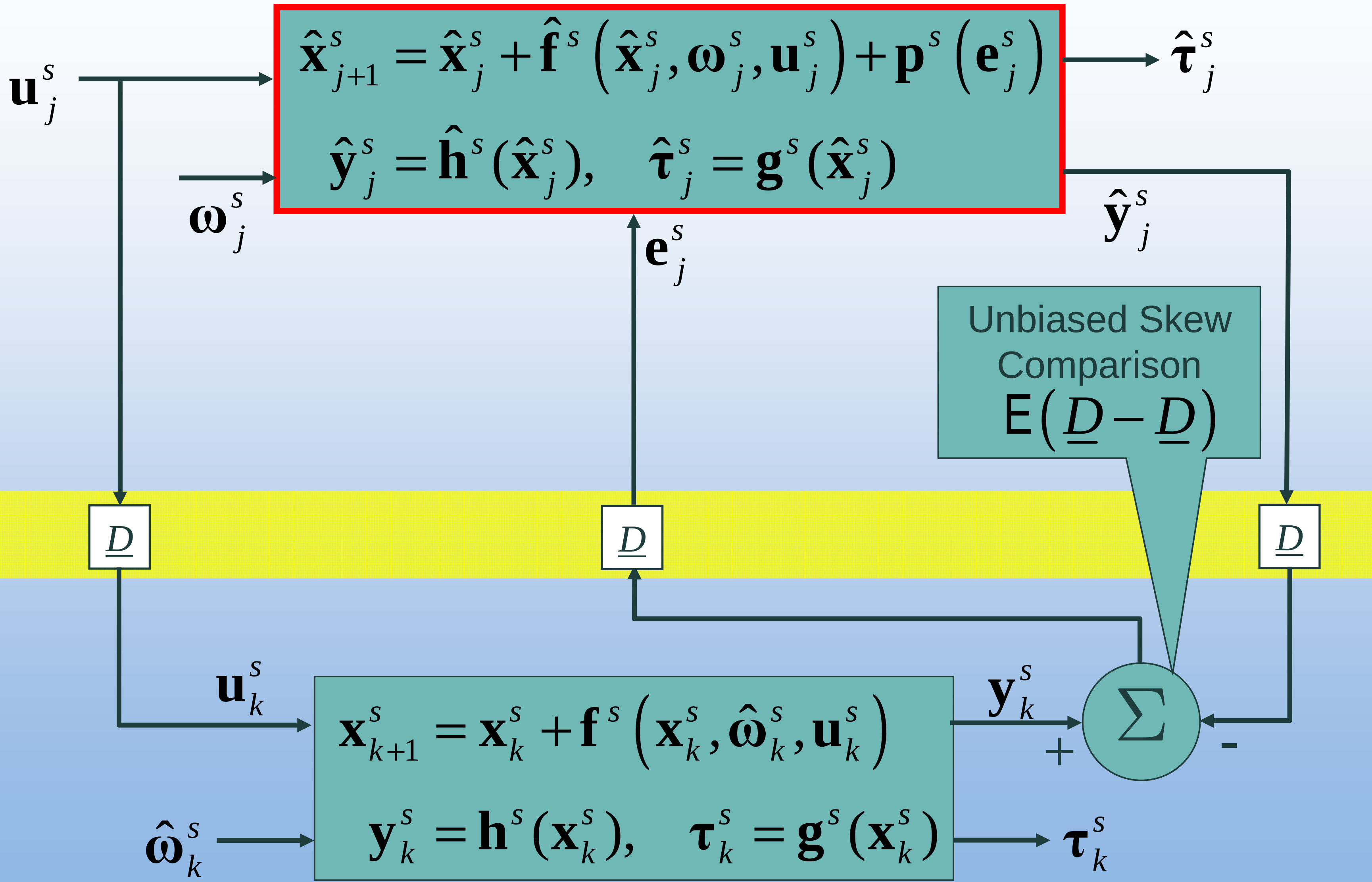
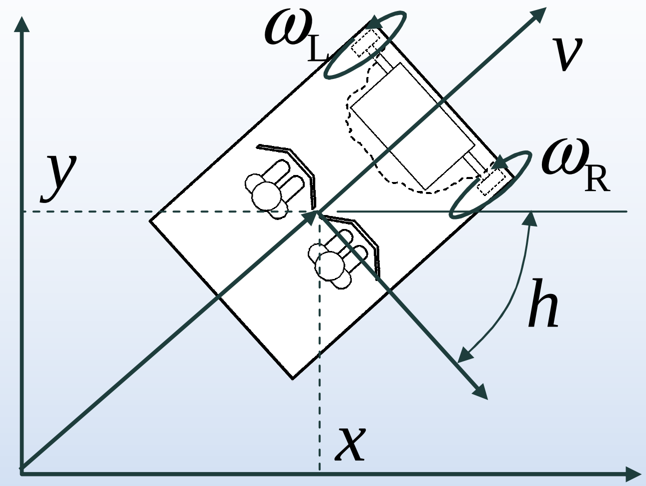
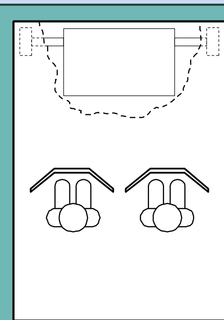
Power Train Observer (un-skewed)



Vehicle dynamics



$$\boldsymbol{\tau}_k^v = \begin{bmatrix} \tau_{\mathrm{L}} \\ \tau_{\mathrm{R}} \end{bmatrix}$$



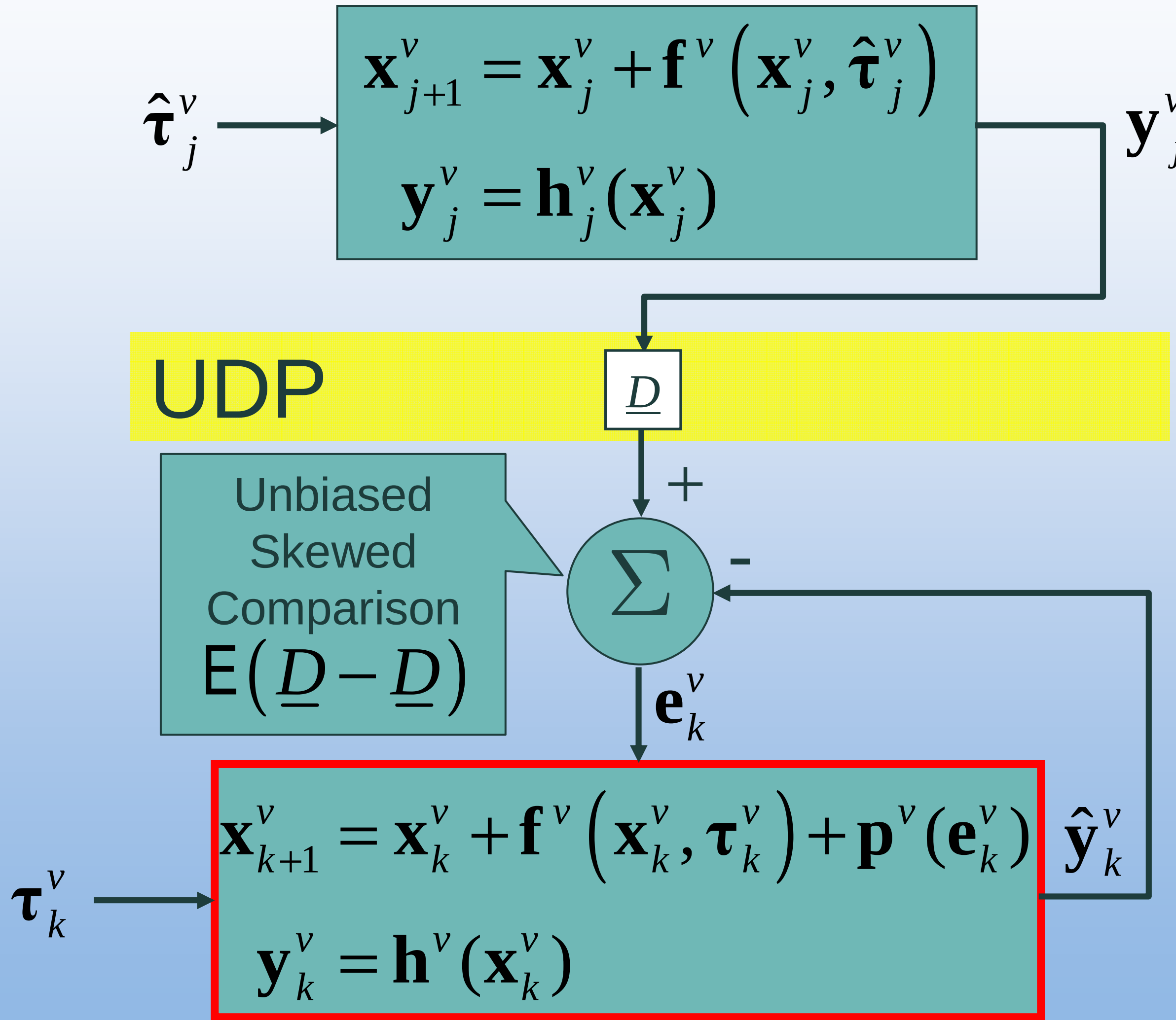
$$\mathbf{x}_{k+1}^v = \mathbf{x}_k^v + \mathbf{f}^v\left(\mathbf{x}_k^v, \boldsymbol{\tau}_k^v\right)$$

$$\mathbf{y}_k^v = \mathbf{h}^v(\mathbf{x}_k^v)$$

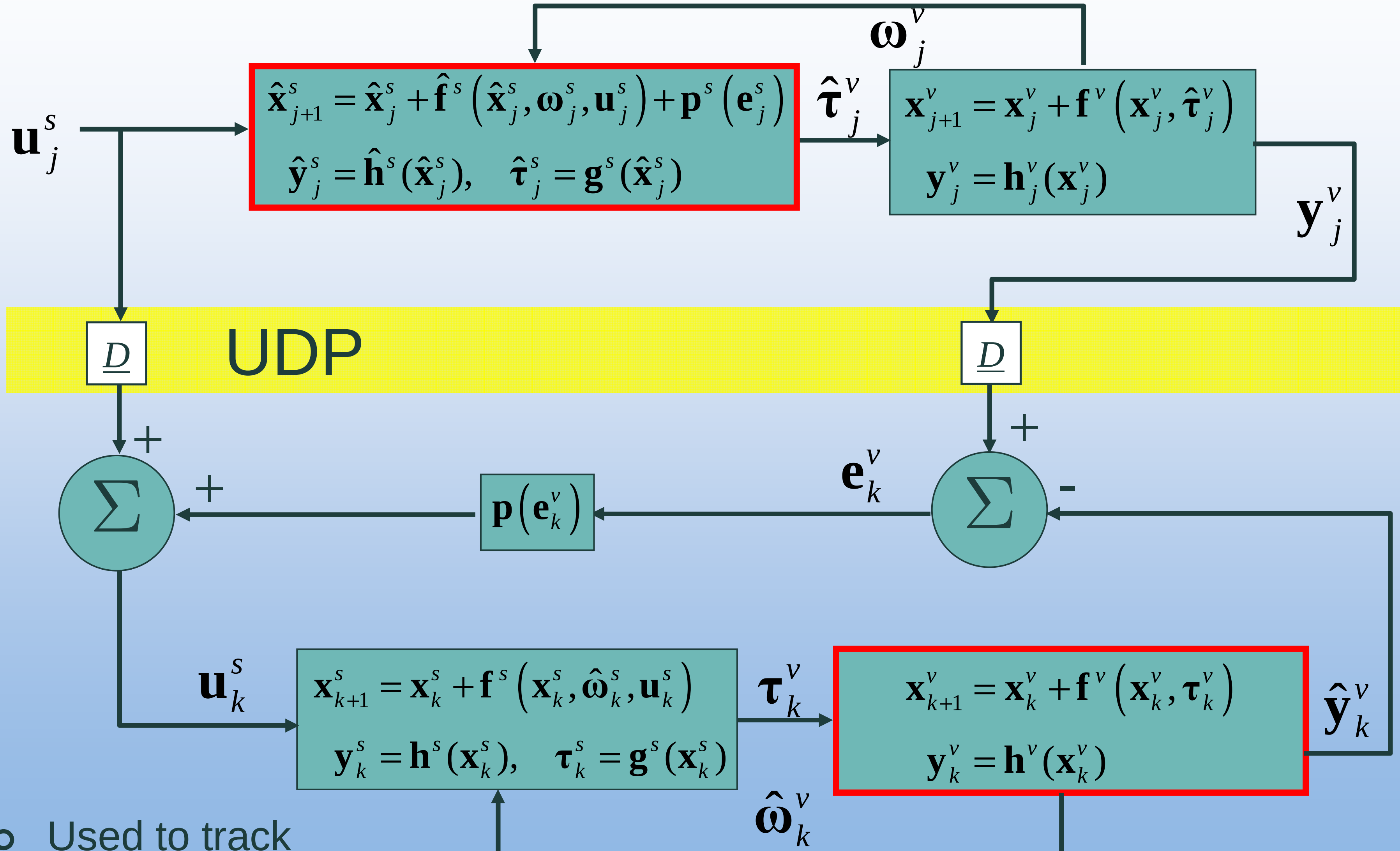
$$\mathbf{y}_k^v = \begin{bmatrix} x \\ y \\ h \\ v \\ \omega_{\mathrm{L}} \\ \omega_{\mathrm{R}} \end{bmatrix}$$

Vehicle Observer – Direct

- Imposes an artificial force on the vehicle
- Used to track
  - Lateral position
  - Heading
  - Sprocket speed



Vehicle Observer – Indirect



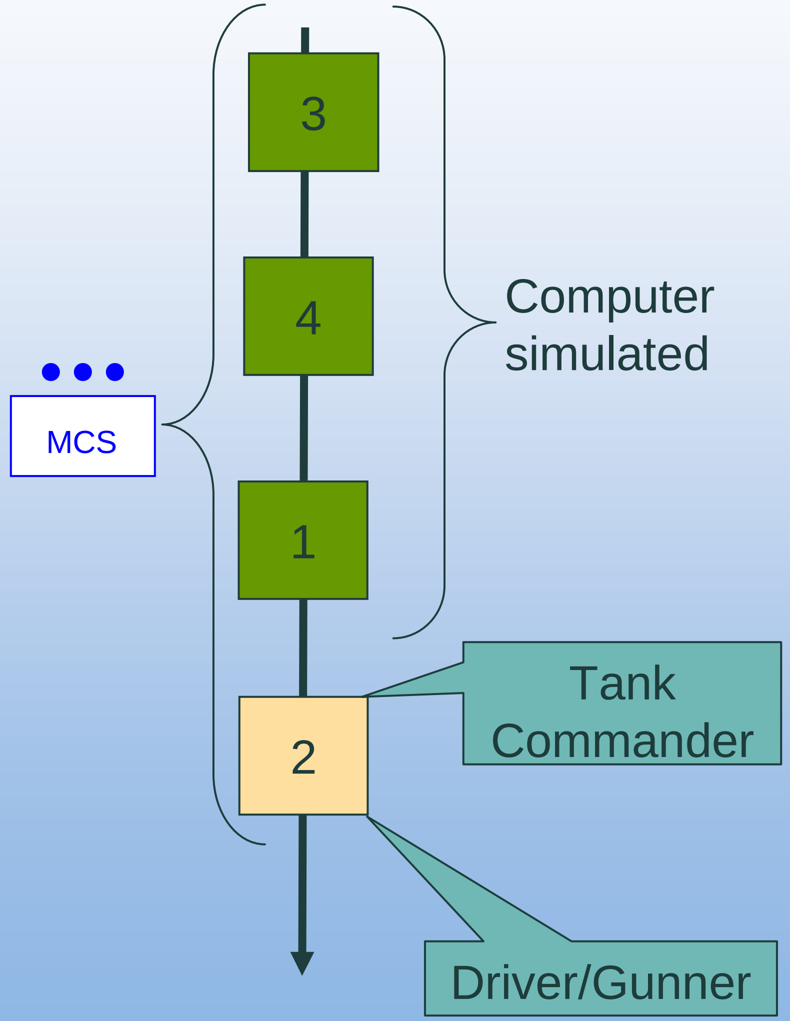
- Used to track longitudinal position

Scenario

- 4 km x 10 km area
- 13 km route
- Grades greater than 30%
- 5 RPG teams encountered on route black
- BMPs encountered after RP
- T80s encountered after BMP engagement.

MCS Platoon as implemented

- Played lead vehicle in the platoon
- Vehicles 1, 3, 4 modeled in OTB in “follow simulator” mode.
- Blue vehicles had little to no impact on behavior of vehicle 2.
- Other blue elements were notional



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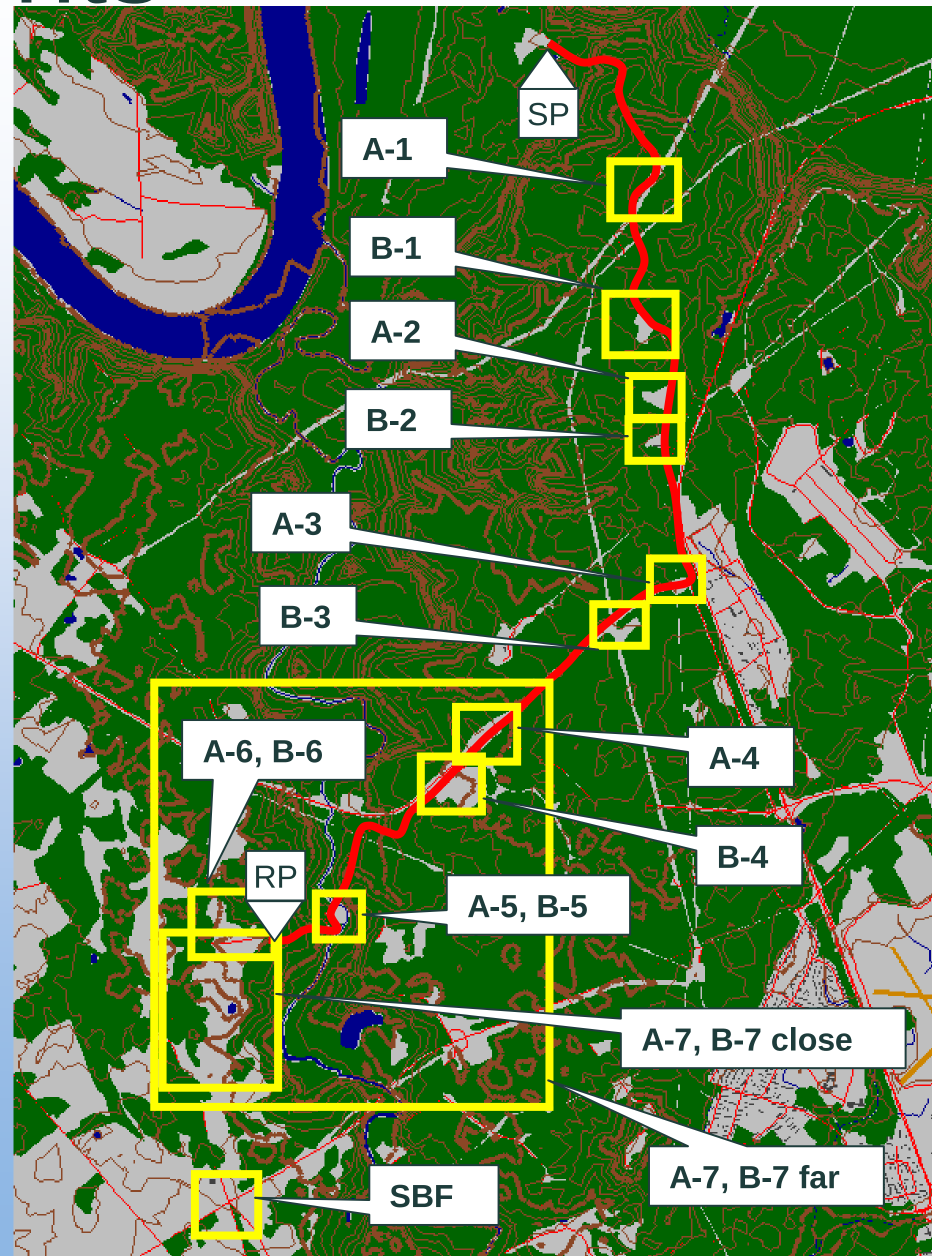
Engagements

Odd Team → Scenario A

Even Team → Scenario B

Engagement	Scenario A	Scenario B
#1	A-1	B-1
#2	A-2	B-2
#3	A-3	B-3
#4	A-4	B-4
#5	A-5	B-5
#6	A-6	B-6
#7	A-7	B-7



Experiment Design

- Each soldier was assigned a subject number S01 – S12
- Soldiers were paired up and allowed to both drive and gun.
- Each configuration was assigned a team number T01 – T12
- Two scenarios used to maintain element of surprise

	Team	Driver	Gunner	Scenario
Week 1 Jun 19-22	T01	S01	S02	A
	T02	S02	S01	B
	T03	S03	S04	A
	T04	S04	S03	B
Week 2 Jun 26-29	T05	S05	S06	A
	T06	S06	S05	B
	T07	S07	S08	A
	T08	S08	S07	B
Week 3 Jul 10-13	T09	S09	S10	A
	T10	S10	S09	B
	T11	S11	S12	A
	T12	S12	S11	B

Experiment Participants

- 11^{th} ACR
- MOS19K
- E7 Proxy Commander
- 12 Participants
  - 1-E4, 6-E5, 5-E6
  - Age [20-34], mean 26.8
  - Avg. time in MOS 6.3 y

Path and grade

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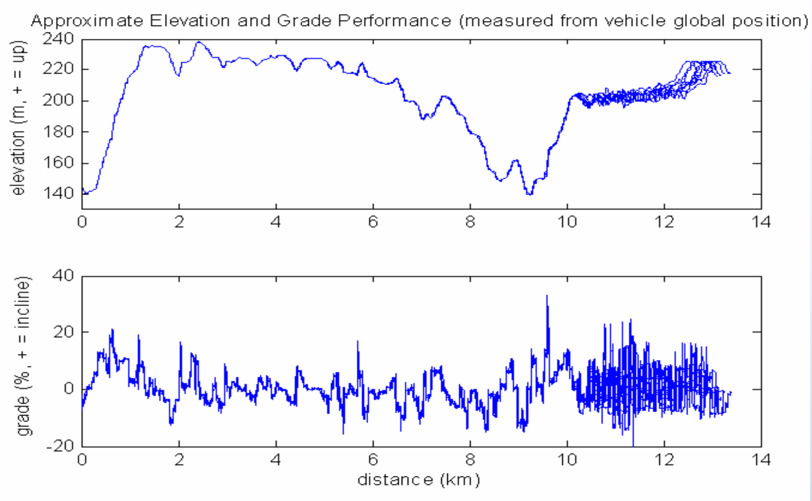
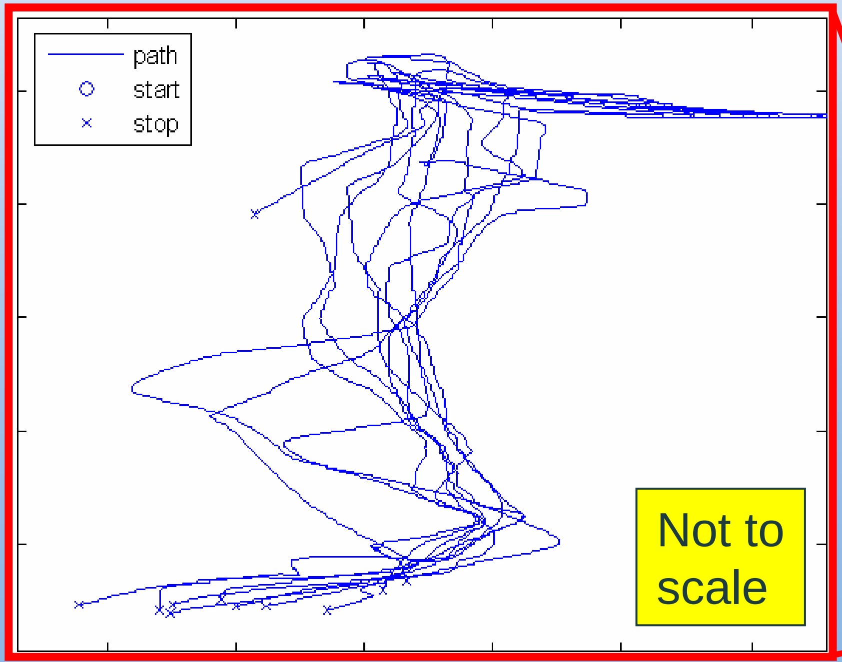
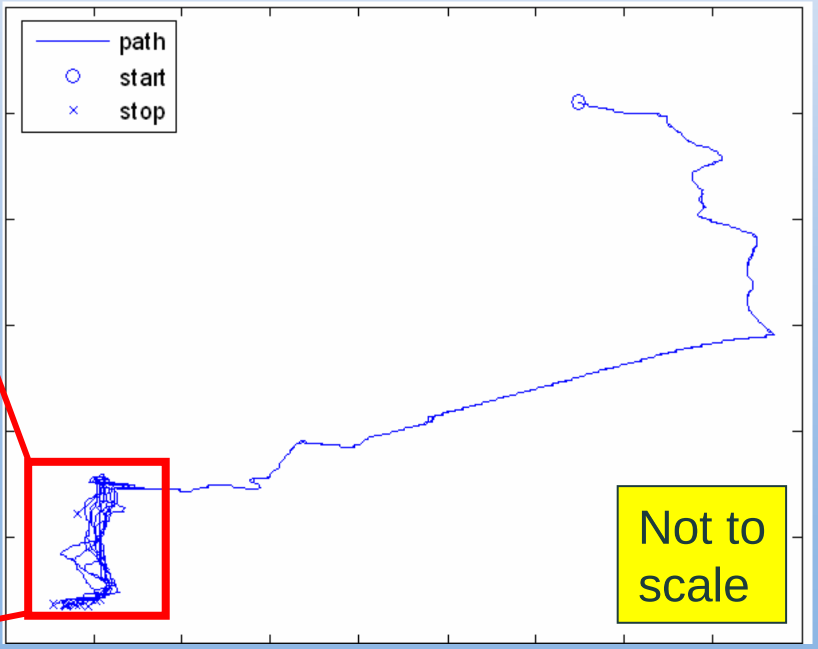
- Shown are the overlaid traces for all 12 runs.
- Variation at the end is due to tactical maneuver.







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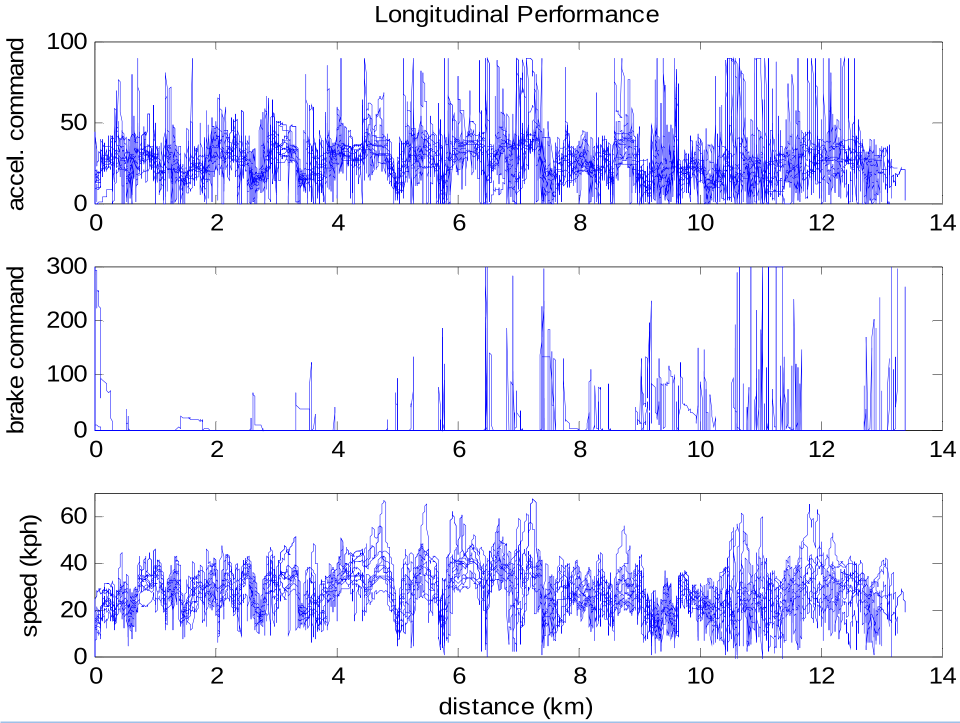
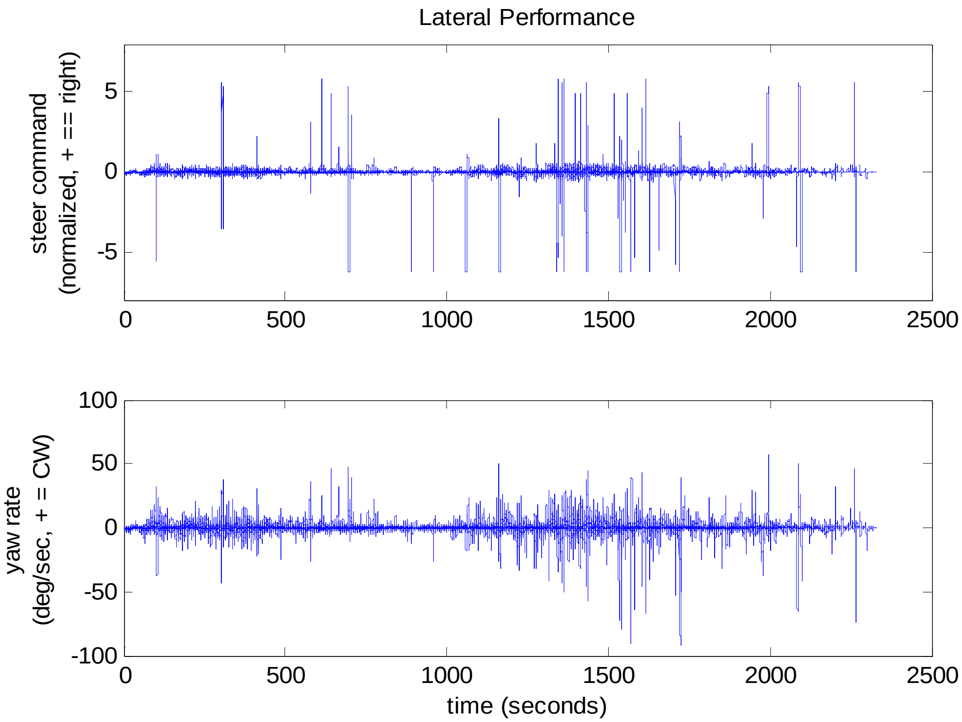
Results: Long & Lat





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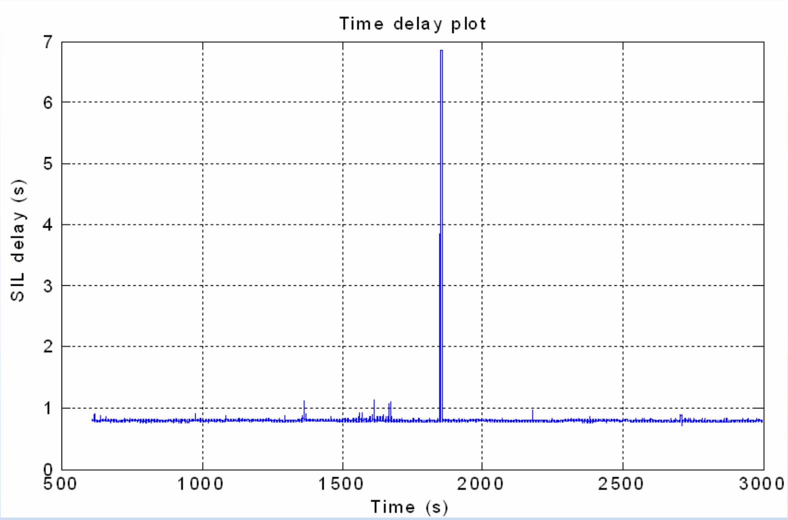
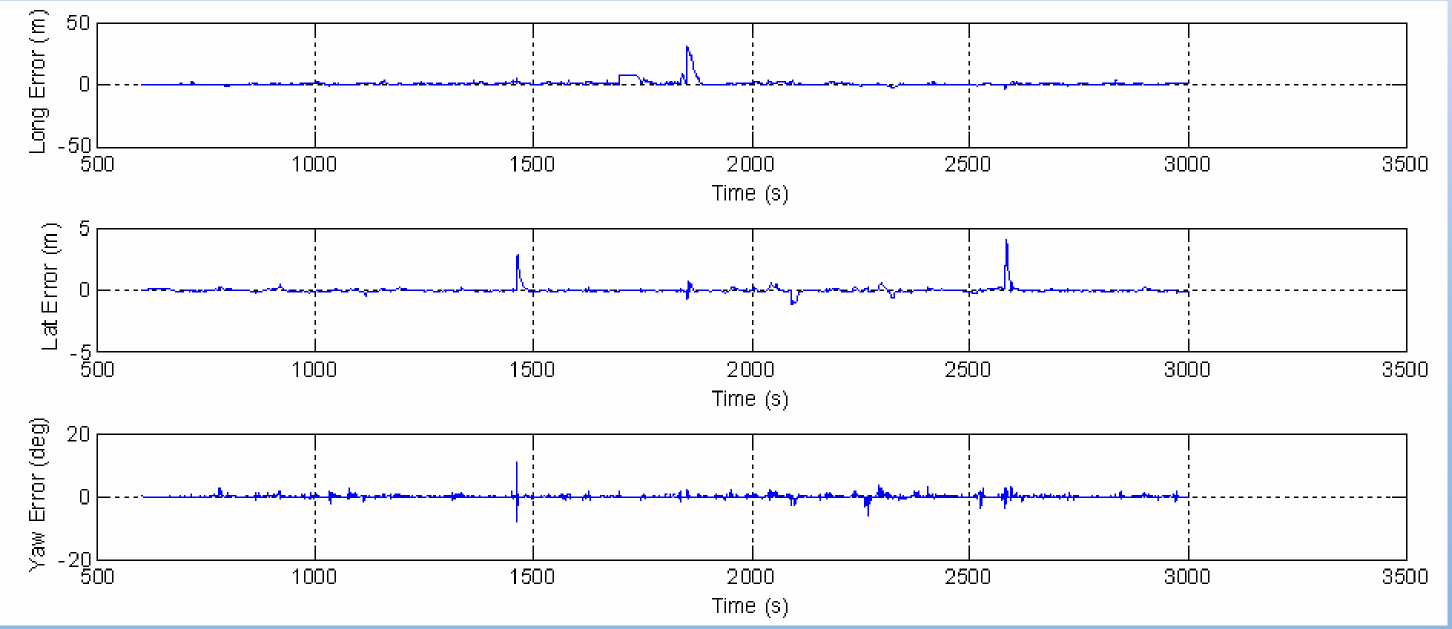
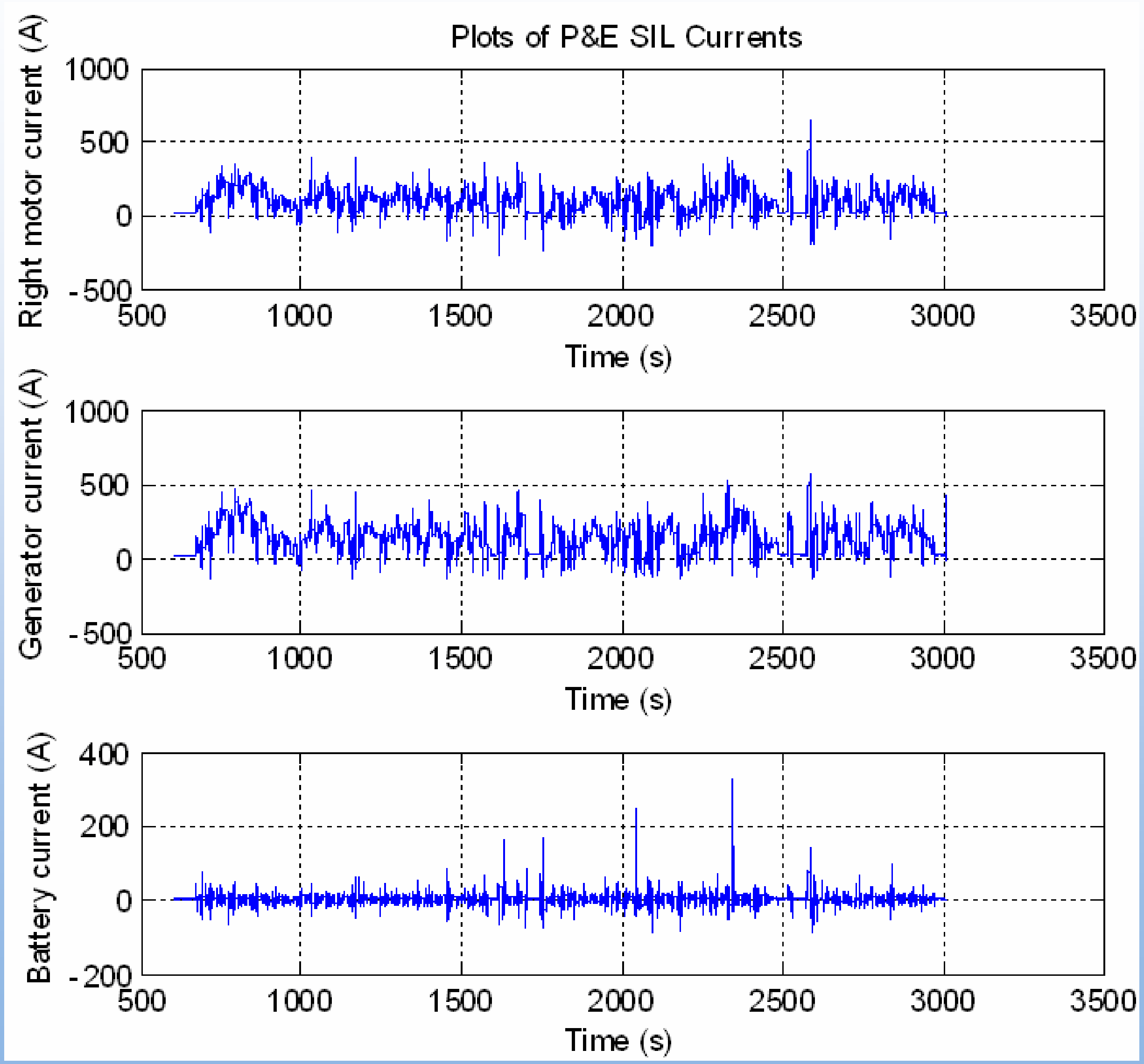
Long Haul Performance

- Typical delay ~ 800 ms
- Experienced outage of ~7 sec.
- Recovered from outage.
- Vehicles tracked well.





SIL Performance



Conclusions & Future Work

- Successfully integrated RMS, vehicle dynamics and CHPS SIL over distance of 2,450 miles
- Implementation based on observers.
- Shown to be robust in the presence of outages.
- A follow-on experiment is planned.

Backup Slides

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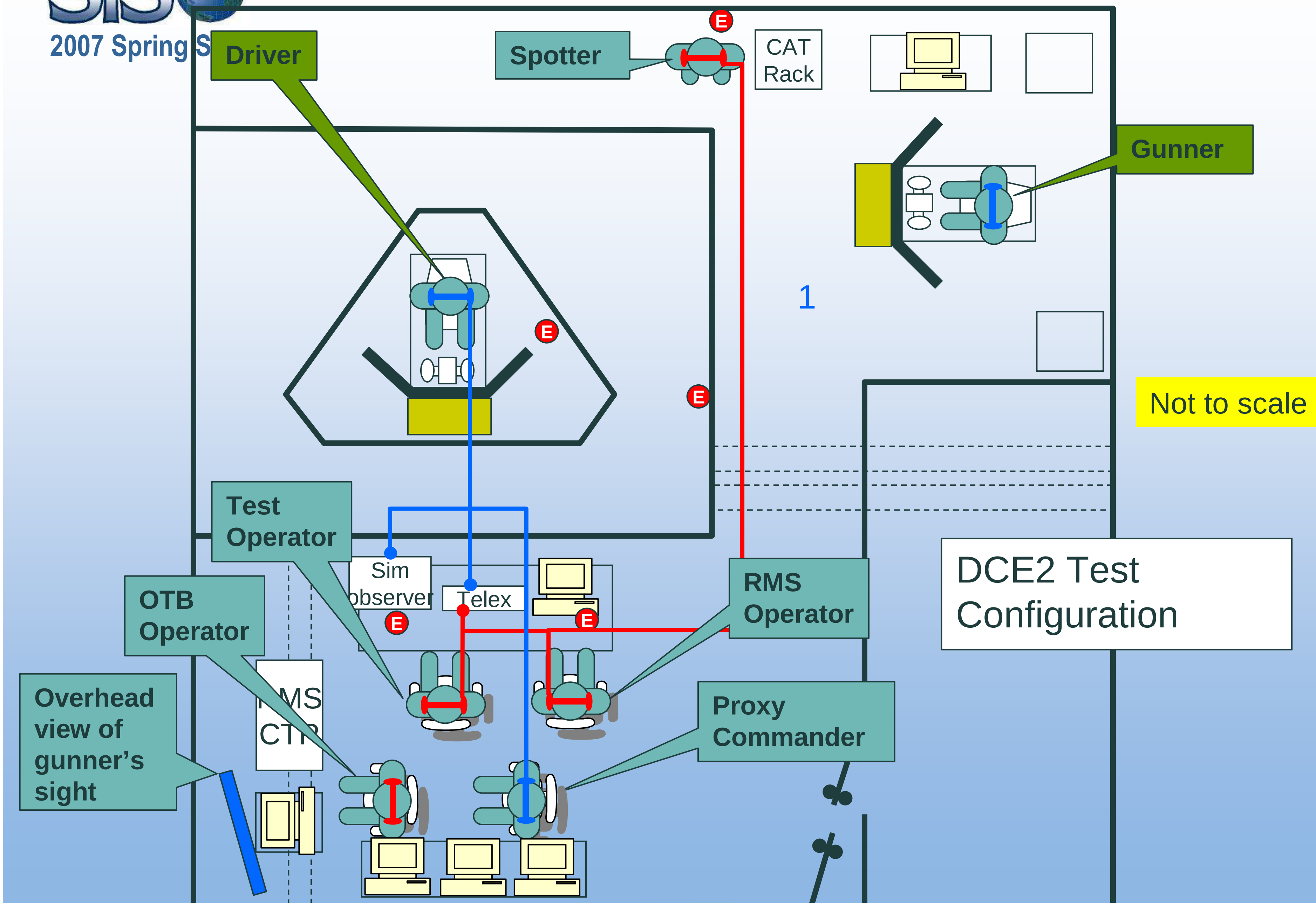
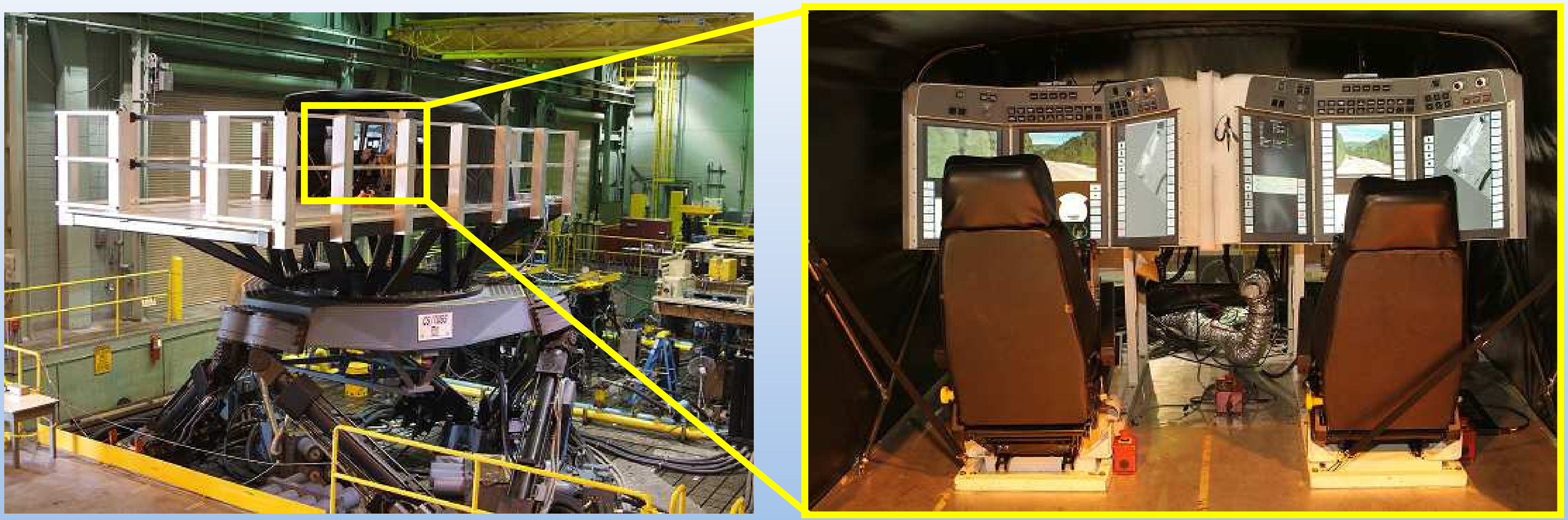


DCE 2.1: TMBS



Data Acquisition

- 293 channels at 50 Hz
  - 21 Power on/off
  - 21 Events
  - 157 Long Haul Channels
  - 28 power system states
  - 42 vehicle states
- External Events
  - Fire events
  - Detonation
- Entity State PDUs
- Video of experiment
- P&E HWIL SIL logged information
- Demographics